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Prediction of Wind Effects on Cold Protective Clothing

Ingvar Holmér[1], Håkan O. Nilsson[1], Hannu Anttonen[2]
[1] Climate Research Group, National Institute for Working Life
171 84 Solna, Sweden
[2] Oulu Regional Institute of Occupational Health, Oulu, Finland

Summary

Cold protective clothing is characterised by its thermal insulation and wind-proof properties. Standard insulation is measured for complete ensembles under static and wind still conditions (ENV-342) Air permeability is measured on the material of the outer layer (ISO-EN-9237). Limited information is available on the interaction of air permeability and thermal insulation under the influence of wind and walking. Ten ensembles comprising 2 to 3-layer combinations with a range of insulation values from 1.49-3.46 clo (0.23-0.54 $m^2°C/W$) and air permeability between 1 and 1000 l/m^2s were measured with a standing and walking thermal manikin. The manikin was placed in a wind tunnel at wind speeds between 0.2-18 m/s. Walking speeds ranged from standing to 1.2 m/s. One equation was derived for prediction of the reduction in thermal insulation value as function of wind, walking and air permeability. The deviation between measured and predicted value was mostly less than 5 % and below 10 %. Air permeability has limited influence in wind speeds below 3 m/s, but becomes progressively important at higher wind speeds. Typically a three layer ensemble with low air permeability will loose 60-70 % of its total insulation in winds of 12 m/s and higher.

The new algorithm for correction of clothing insulation has been incorporated in (ISO/CD-1179) and subsequently, allows more realistic

- prediction of heat balance in cold environments and operational capabilities
- analysis of the risks associated with extreme cold and wind conditions
- assessment of the protective function of available cold weather ensembles.

Introduction

Air temperature and wind are the two most important climatic factors determining heat losses from humans in cold environments. Studies have shown that the protective value of clothing may reduce considerably under the influence of wind (Afanasieva 1992; Havenith et al. 1990; Mäkinen et al. 1998; Mäkinen et al. 2000; Mäkinen et al. 1997; Nilsson et al. 2000; Pugh 1966; Wilson et al. 1970). Few studies, however, report systematic effects over a wide range of wind velocities.

Cold protective clothing is characterised by its thermal insulation and wind-proof properties. Standard insulation is measured for complete ensembles under static and wind still conditions (ASTM-F1291 1995; ENV-342 1999). Air permeability is measured on the material of the outer layer (ISO-EN-9237). Limited information is available on the interaction of air permeability and thermal insulation under the influence of wind and walking.

This paper reports the result of two studies of wind effects on different types of clothing ensembles, carried out with a moveable thermal manikin. Parts of them have been published (Holmér et al. 1992; Nilsson et al. 1998; Nilsson et al. 1992)

Material and methods

Ten ensembles comprising 2- to 3-layer combinations with a range of total, static insulation values from 1.49-3.46 clo (0.23-0.54 $m^2°C/W$) were measured. Six of them were measured in a climatic chamber where wind could be controlled between 0.2 and 1.0 m/s (Nilsson et al. 1992). Four ensembles were measured in a climatic chamber with a built-in wind tunnel over the range of 0.4 to 18 m/s (Nilsson et al. 1998). The four ensembles comprised 3-layer systems with different outer garments. The air permeability of the outer garments varied between 1 and 1000 l/m^2s. In both studies measurements were also made with the manikin nude.

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The manikin comprised 18 zones, heated by a computer regulated power supply from an electric power box. Skin temperature was individually controlled and maintained at 34.0 °C. The manikin was placed in a wind tunnel at wind speeds between 0.4-18 m/s. Walking speeds ranged from standing to 1.2 m/s. Walking speed was determined from step length and step frequency. Manikin heat loss was monitored and a valid record was obtained when it had reached steady state (approx. after 40-60 minutes). Manikin and procedures have been reported earlier (Nilsson et al. 1997). The manikin can simulate walking movements by a pneumatic lever system (Figure 1).

$$I_{Tot} = \frac{34 - t_a}{Q_{Tot}} \cdot A_d \qquad (1)$$

The total insulation value was calculated by equation 1. I_{Tot} is the total insulation value in m^2°C/W, 34 is the controlled manikin surface temperature in °C, t_a is the ambient air temperature in °C, Q_{Tot} is the sum of all zone heat losses in W, and A_d is the manikin surface area in m^2. The repeatability of the method, used for determination of insulation values, is high. The difference between double determinations was less than 5% of the mean value of the two measurements based on 228 independent measurements. Insulation values are often reported as clo-values – 1 clo=0.155 m^2°C/W.

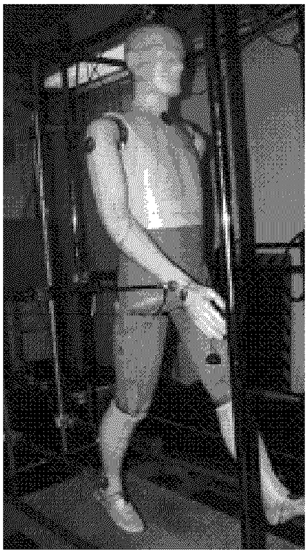

Figure 1. Walking, thermal manikin "TORE" used in the two wind studies.

Results and discussion

The regression equations obtained with the two sets of data from quite different range of air velocities were remarkably similar. In the range 0.2-1 m/s there was little variation between types of clothing in relative reduction. Data were pooled with the results from the second study with a much larger range of wind velocities. The general equation derived from this data set of 228 independent measurements showed a correlation coefficient of 0.91. The general equation has the form

$$I_{t,r}/I_t = A \cdot e^{(B \cdot v + C \cdot w)} \qquad (2)$$

Figure 2 shows the reduction in insulation value for four ensembles at air velocities from 0.4 to 18 m/s. The reduction is expressed as fraction of the value at 0.4 m/s. The four ensembles represent similar types of 3-layer systems, but with different material in the outer layer. There is a clear difference between ensembles, in particular at higher wind velocities.

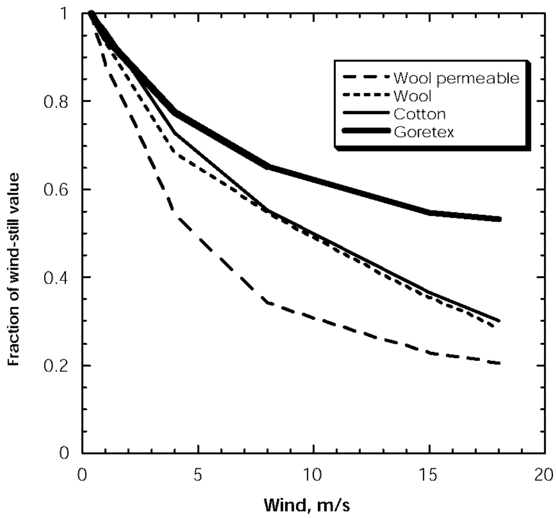

Figure 2. Reduction of total insulation of four types of winter clothing ensembles as function wind speed. Measurements were taken with a thermal manikin in a climatic wind tunnel.

At higher air velocities an equation with only wind and walking as variables becomes insufficient. An obvious reason for this is the air permeability of the outer layer. This material property becomes an important determinant of wind penetration into the clothing layers and subsequently affects the heat losses. Air permeability was introduced in the regression analysis and new equation was derived with the three variables.

The insulation reduction ($I_{t,r}/I_t$) as a function of air permeability (p, l/m^{2}s), wind speed (v, m/s) and walking speed (w, m/s) based on the present data set of is now calculated with:

$$I_{t,r}/I_t = 0.54 \cdot e^{(-0.15 \cdot v - 0.22 \cdot w)} \cdot p^{0.075} - 0.06 \cdot \ln(p) + 0.5 \qquad (3)$$

The equation is derived from three dependent regressions, one for wind and walk (R = 0.885) and one for the inclination of the permeability (R = 0.965) and one for the intercept of the permeability (R = 0.998). The standard deviation of the difference between measured and calculated data ($I_{t,r}/I_t$) is 4% (Max/Mean/Min 15/5/0) based on all 228 independent data sets. The maximum, mean and minimum difference are 15, 5 and 0 %, respectively. The valid interval for the equation is 0.4-18 m/s wind speed, 0-1.2 m/s walking speed and an air permeability of 1 to 1000 l/m^{2}s. The equation is plotted in figure 3 for a low and a high value for the air permeability of the outer layer.

Air permeability has limited influence in wind speeds below 3 m/s, but becomes progressively important at higher wind speeds. Typically, a 3-layer ensemble with high air permeability will loose 60-70 % of its total insulation in winds of 12 m/s and higher (figure 3). Also highly impermeable ensembles will loose 30-40 % at high wind speeds, mostly as a result of boundary layer breakdown and compression effects.

Few data are reported in the literature on effects at high wind speed. Breckenridge and Goldman (Breckenridge et al. 1977) derived specific correction equations for defined military ensembles. At 10 m/s the winter ensemble reduced by about 20 % and the standard fatigues with over-garment reduced by about 40 %. Reductions are a little bit smaller than reported here (Figure 3), but a direct comparison cannot be made, as the details of the ensembles are not known. Afanasieva (Afanasieva 1992) reported wind effects of similar magnitude to those reported here.

Wyon (Wyon 1989) made a series of measurements with a thermal manikin in a small wind tunnel and reported the results as wind chill equations for typical civilian, outdoor clothing. He concludes that the wind-chill temperature for the clothed body is much lower, than for nude skin. This is in clear contrast to the results of this and other studies (Breckenridge et al. 1977; Steadman 1971; Steadman 1984). His results show

remarkable reductions also for heavy winter clothing. The temperature for good heat balance would need to be +2 °C for jogging at 220 W/m^2 in a wind of 2.5 m/s dressed in an ensemble with a total, static insulation value of 2.6 clo (0.403 m^2°C/W). This is in clear contrast to common experience. Using the IREQ-index (ISO/CD-11079 2000) for the given conditions gives a balance temperature of –23 °C. Making the unlikely assumption that the specified down jacket is highly air permeable (500 l/m^{2}s), still gives a balance temperature of –18 °C.

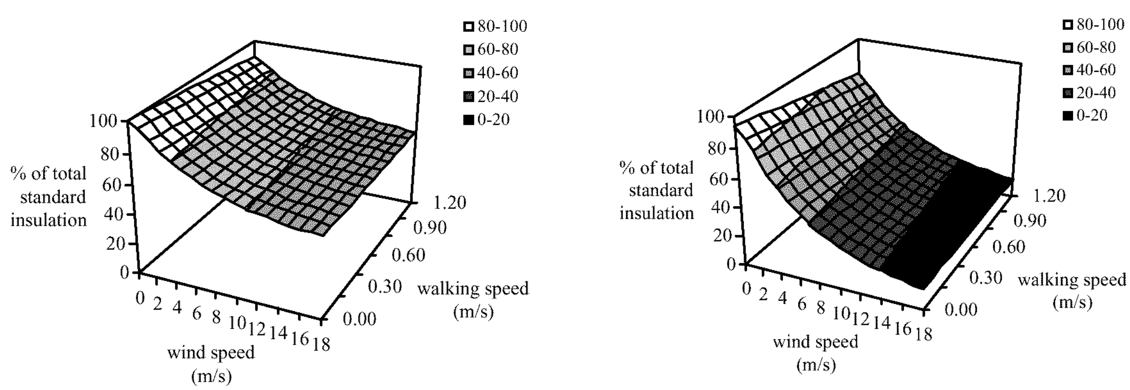

Figure 3. The combined effect of wind and walking speed on the total insulation value of 2-3-layers clothing ensembles. Air permeability of the outer layer is 1 (left panel) and 1000 l/m^{2}s (right panel), respectively (Nilsson et al. 2000).

The new correction algorithm is used in the revised version of the IREQ-index (ISO/CD-11079 2000). The value of IREQ is still the same (figure 4), because this is the resultant insulation that must be provided by clothing independent of type, material and wind. In order to analyse if the selected (worn) clothing ensemble satisfies the requirement (IREQ-value), the insulation reduction as a result of the given conditions (activity and wind) and the material air permeability must be calculated. This is done automatically in the computer program. This means that the selected clothing maybe required to have a static insulation value that can be more than 2 times higher than the IREQ-value, in particular if wind speed is high and air permeability is high (figure 3). In other words, when tested according to ENV-342 (ENV-342 1998) or ASTM-F1290 (ASTM-F1291 1995) the ensemble gets an insulation value for static, wind-still conditions. This value will then be corrected in the IREQ-analysis using the new algorithm.

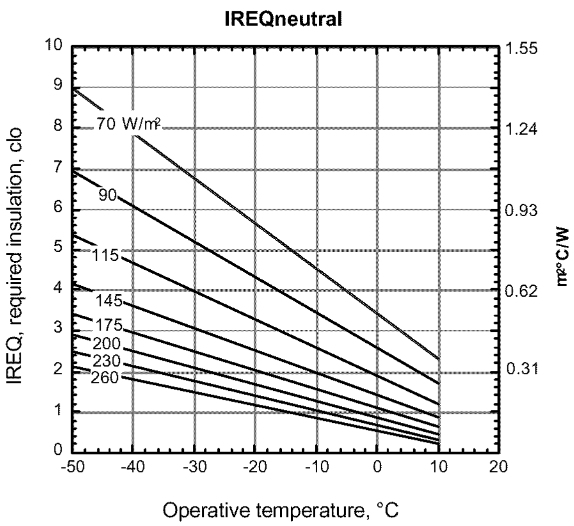

Figure 4. IREQ$_{neutral}$ as function of ambient operative temperatureat eight levels of metabolic heat production. IREQ is specified for thermoneutral conditions of the heat balance. This would correspond to a thermal sensation of neutral to slightly warm. Values apply to wind-still conditions.

In conclusion, one equation has been derived for prediction of the reduction in thermal insulation value of 2-3-layers clothing ensembles as function of wind, walking and air permeability. The deviation between measured and predicted value was mostly less than 5 % and below 10 %. The air permeability has little influence on the insulation for wind speed below 3 m/s. For calculations below such a limit the air permeability could be omitted. In the future only measurements on a standing manikin should be needed. The wind, permeability and walk reductions will be calculated from this value. To validate the relationships more measurements on subjects exposed to wind and activity in working life are needed. This is the subject of a recently started EU-research project. Albeit, the correction algorithm is based on a large database, results from the testing of new materials and ensembles, may modify the basic equation.

The new algorithm for correction of clothing insulation allows more realistic
- prediction of heat balance in cold environments and operational capabilities
- analysis of the risks associated with extreme cold and wind conditions
- assessment of the protective function of available cold weather ensembles.

Acknowledgement

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